Overview of MR Physics

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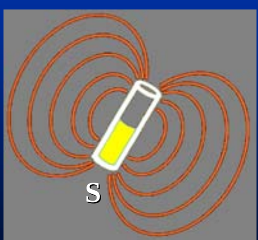
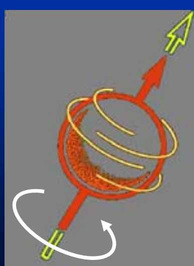
National Center for Research Resources

Outline

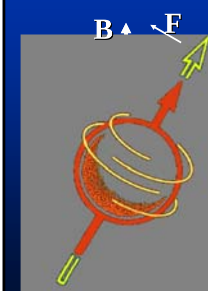
- NMR
  - magnetic moment and angular momentum
  - effects of applied magnetic field
  - excitation and FID
  - spin echo
  - T_1, T_2, and T_2^*
- MRI
  - spatial localization using gradients
  - introduction to k-space

Nuclear Spin and Magnetic Moment



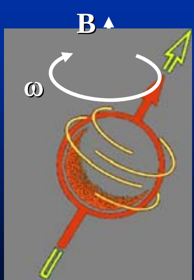


Nuclear Spin and Magnetic Moment



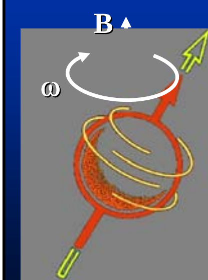
- An external magnetic field B will apply a force perpendicular to μ

Nuclear Spin and Magnetic Moment



- A force perpendicular to I will cause a torque
- To conserve angular momentum the spins rotate about B

Nuclear Spin and Magnetic Moment



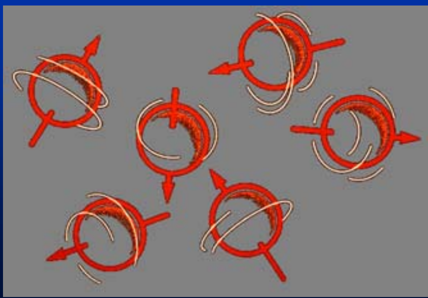
- Spins rotate about B at a frequency proportional to B

$$\omega = \gamma B$$

(Larmor frequency)
- gyromagnetic ratio γ depends on nucleus
- for protons (H^1)

$$\gamma = 42.6 \text{ MHz per Tesla}$$

Randomly oriented spins

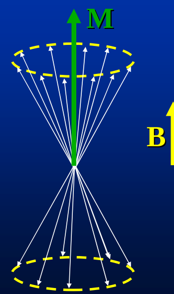


Net magnetization

Net magnetization M proportional to B

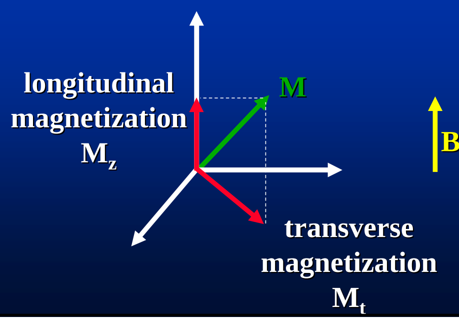
M=0 at B=0

At 1.5 T (15,000 gauss) preferential alignment is 5 per million



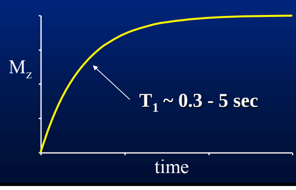
NMR for Basic MRI

Net magnetization

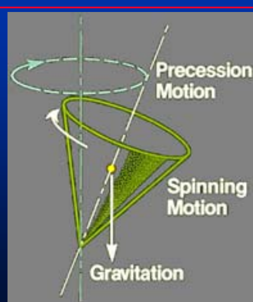


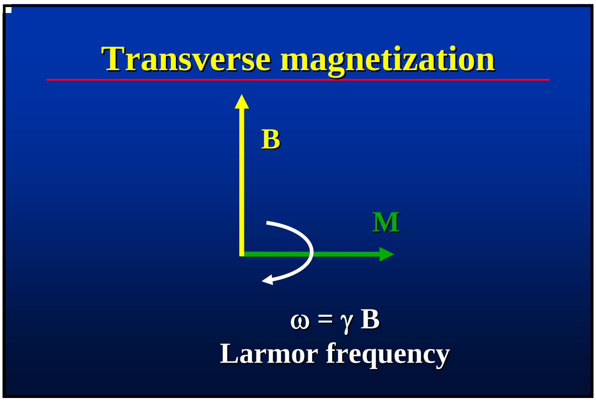
Longitudinal magnetization, M_z and T_1 recovery

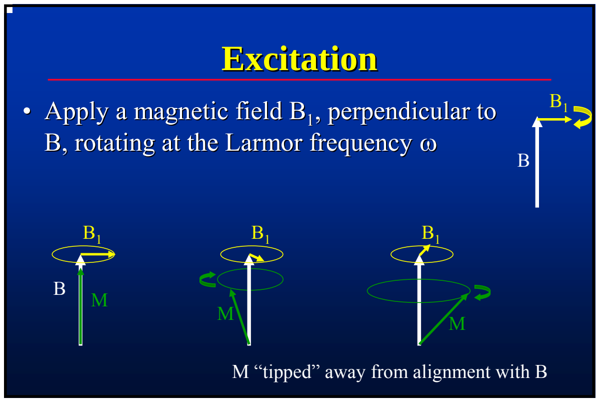
- magnetization in the direction of main field B
- equilibrium M_z = N(H)
- if $M_z \neq N(H)$, it will approach N(H) with time constant T_1

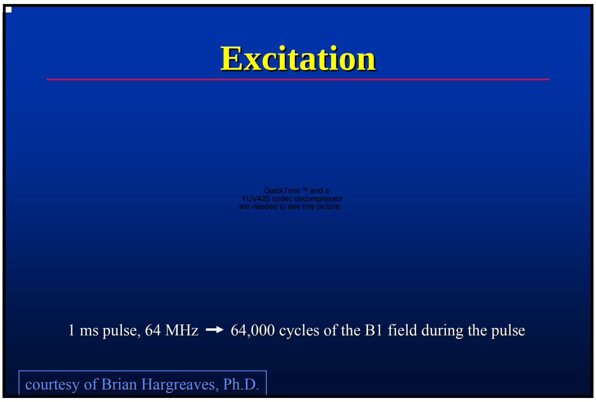


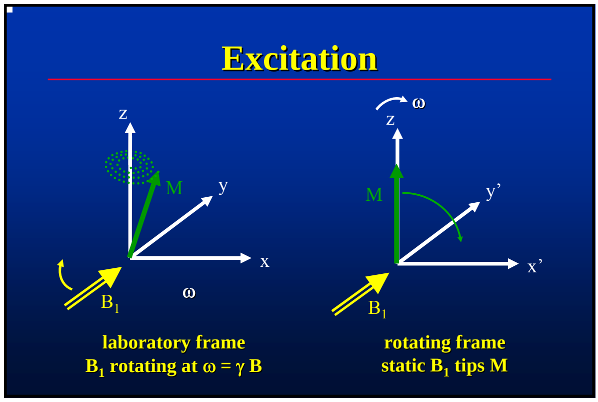
Precession in a gravitational field

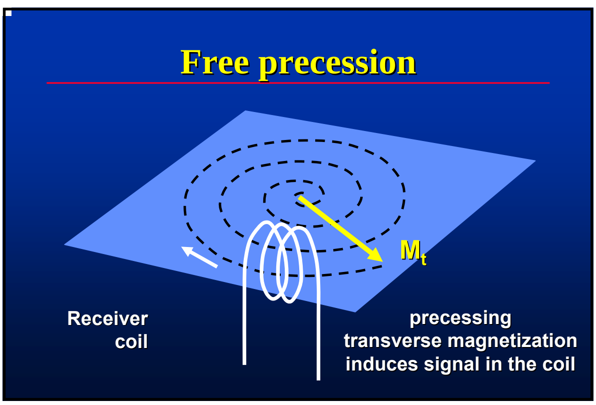


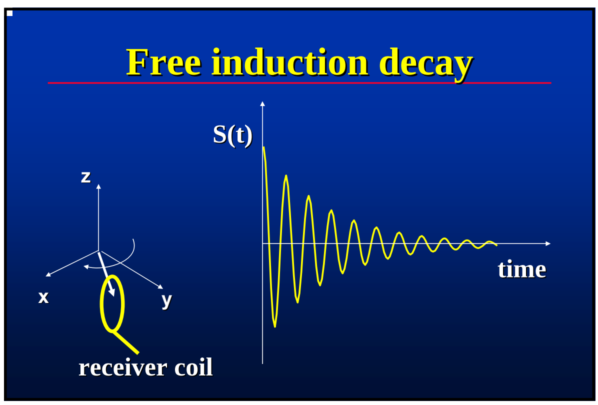

Transverse magnetization
B
M
ω = γ B
Larmor frequency


Excitation
• Apply a magnetic field B1, perpendicular to B, rotating at the Larmor frequency ω
B1
B
B1
B
M
B1
M
B1
M
M "tipped" away from alignment with B


Excitation
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
1 ms pulse, 64 MHz → 64,000 cycles of the B1 field during the pulse
courtesy of Brian Hargreaves, Ph.D.


Excitation
z
M
y
x
B1
ω
ω
z
M
y'
x'
B1
laboratory frame
B1 rotating at ω = γ B
rotating frame
static B1 tips M


Free precession
Mt
Receiver coil
precessing transverse magnetization induces signal in the coil

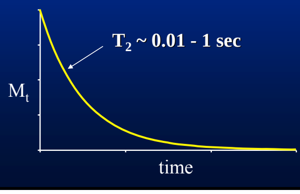

Free induction decay
S(t)
z
x
y
time
receiver coil

Transverse magnetization, M_t and T_2 decay

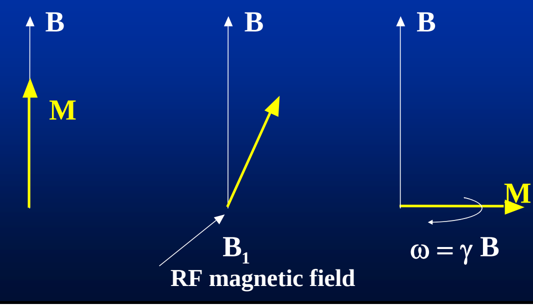
- magnetization perpendicular to main field B
- equilibrium $M_t = 0$
- if $M_t \neq 0$, it will:

rotate about B at $\omega = \gamma$ B

decay with time constant T_2



Classical view of NMR



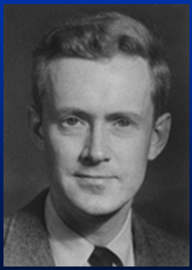
Classical view of NMR

- Transverse magnetization decays with time constant T_2
- Longitudinal magnetization recovers with time constant T_1

Nuclear Magnetic Resonance

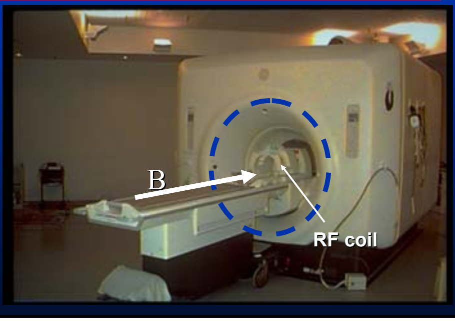
1952 Nobel Prize in Physics

Felix Bloch
1905-1983



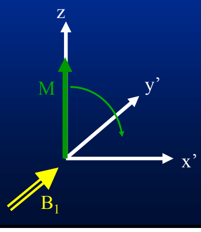
Edward M. Purcell
1912-1997

Hardware

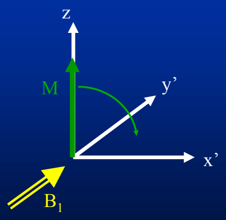


RF pulse

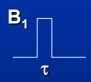
- pulsed magnetic field rotating at ω
- called "RF" pulse because ω is in the radiofrequency range
- it is not a radio wave
- rotates component perpendicular to B_1
- flip angle
- phase or direction



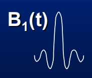
Flip angle



rotating frame
static B_1 tips M

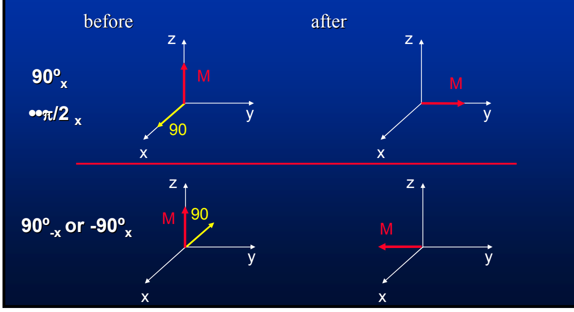


$\alpha = \gamma B_1 \tau$

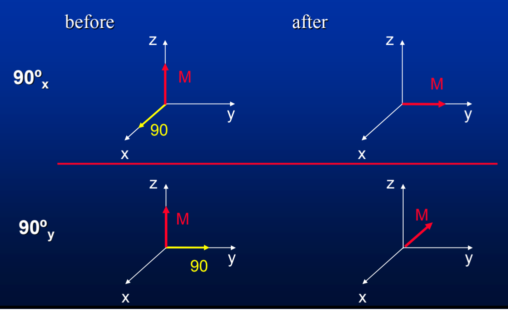


$\alpha = \gamma \int B_1(t)\, dt$

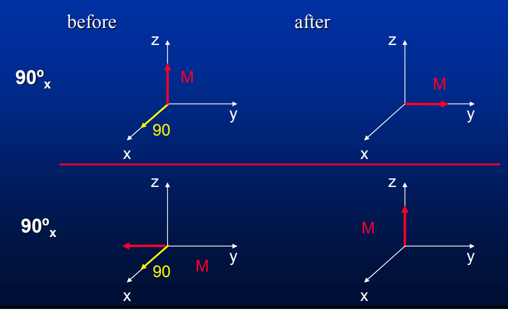
direction or phase



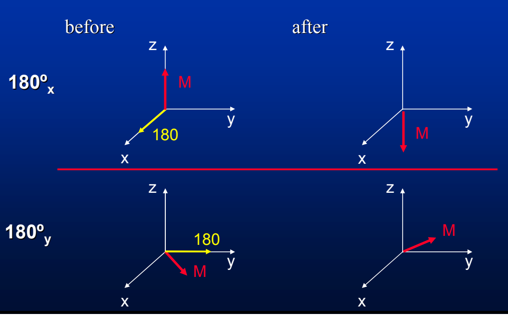
direction or phase



direction or phase



RF pulses



Longitudinal magnetization, M_z and T_1 recovery

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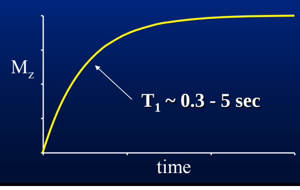
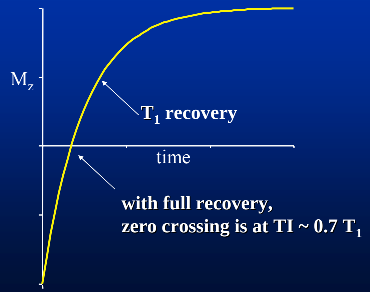
- if $M_z \neq N(H)$, it will approach N(H) with time constant T_1



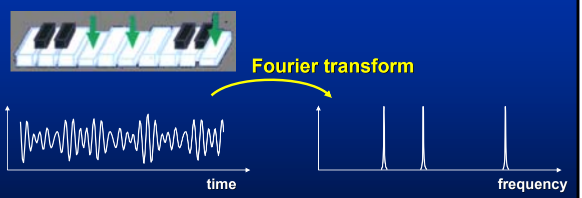
Inversion recovery



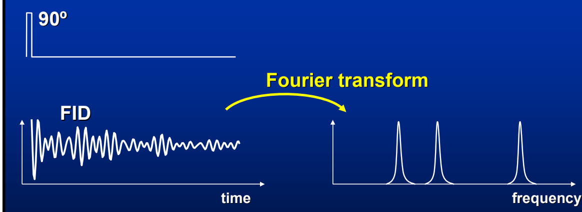
Off-resonance

- offset in resonant frequency
- chemical shift
- magnetic field inhomogeneity

Piano analogy

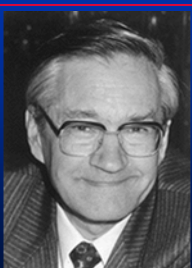


Fourier transform NMR



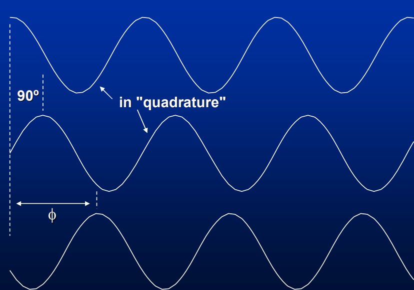
Nuclear Magnetic Resonance

1991
Nobel Prize
in
Chemistry



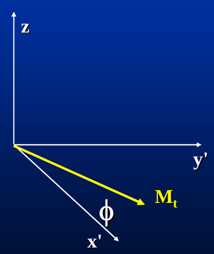
Richard R. Ernst
1933 -

signal phase

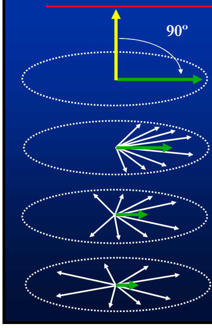


MR signal is a vector quantity

- magnitude (M_t)
- phase (ϕ)
- phase is affected by resonance offset

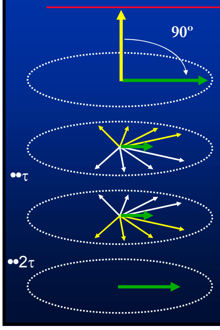


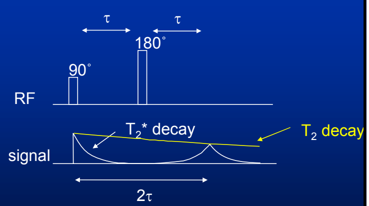
Net transverse magnetization



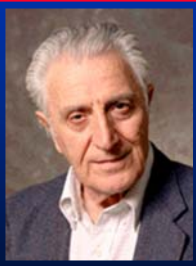
- T_2 (and T_2*) decay is a bulk phenomenon
- "spin isochromat" groups
- M_t of each isochromat shortens (random spin-spin effects)
- isochromats dephase -> signal decays with $T_2^* \leq T_2$

Spin-echo



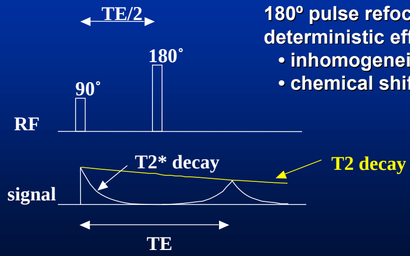


Nuclear Magnetic Resonance



Erwin L. Hahn

Spin-echo



180º pulse refocuses deterministic effects:
- **inhomogeneity**
- **chemical shift**

T_2 *vs* T_2*

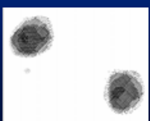
- $T_2^* < T_2$
- T_2* includes the effects of inhomogeneity

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2'}$$

- T_2' effect recovered by 180º pulses

Magnetic Resonance Imaging

2003
Nobel Prize
in Medicine

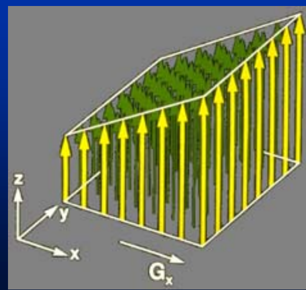


Lauterbur,
Nature 242, 190, 1973

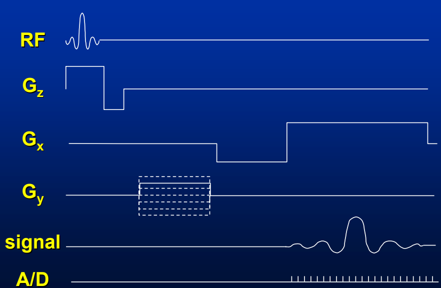
Paul C. Lauterbur

Sir Peter Mansfield

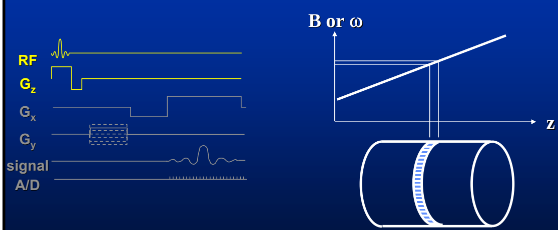
Gradient of the magnetic field



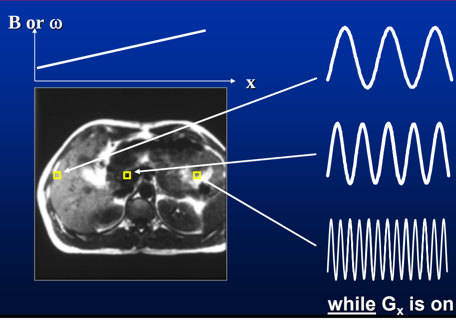
MRI pulse sequence



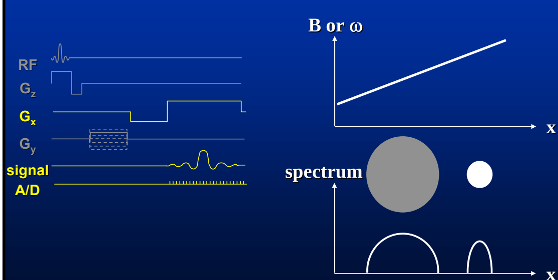
Selective excitation



Frequency encoding

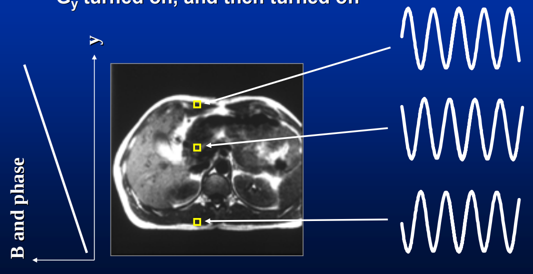


Frequency encoding

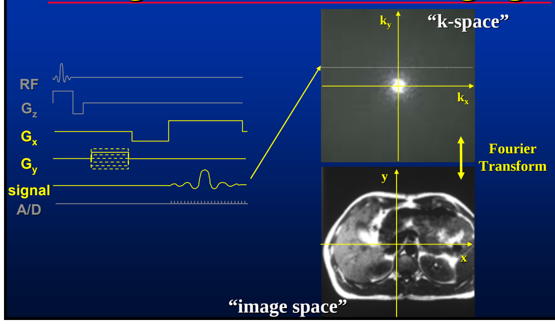


Phase encoding

G_y turned on, and then turned off

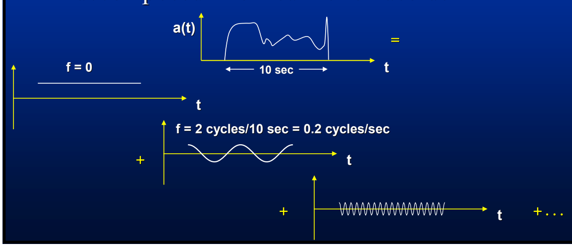


Magnetic Resonance Imaging

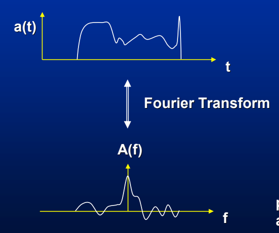


Frequency analysis

- (Almost) any 1-dimensional signal can be decomposed into a sum of sinusoids



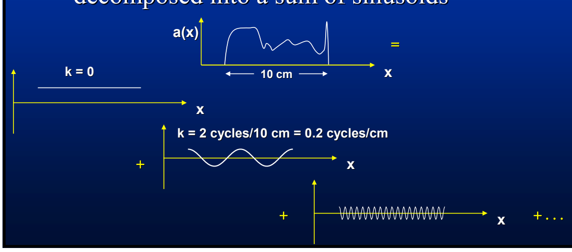
Frequency analysis



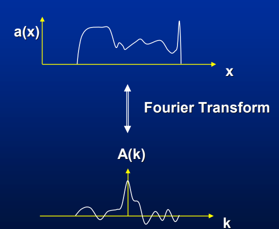
positive & negative frequencies allow arbitrary phase sinusoids

1-dimensional "image"

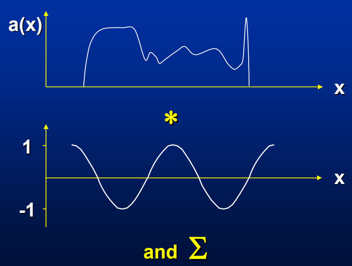
- (Almost) any 1-dimensional signal can be decomposed into a sum of sinusoids



1-dimensional "image"

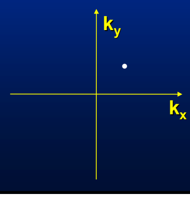


calculate Fourier coefficient

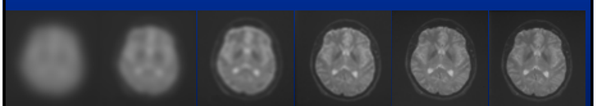


calculate 2D Fourier coefficient

$$A(k_x, k_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} a(x,y)\, e^{i(k_x x + k_y y)}\, dx\, dy$$

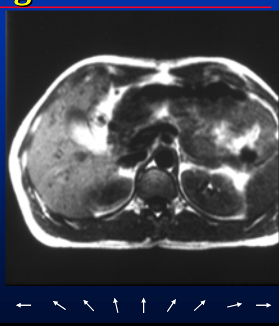


spatial frequencies

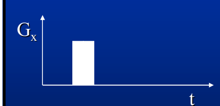


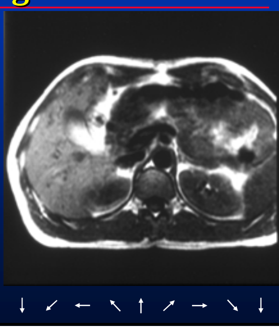
additional spatial frequencies →

effect of gradients

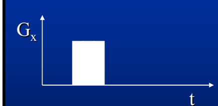


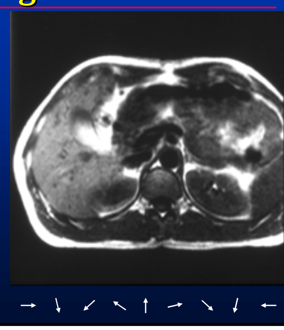
effect of gradients

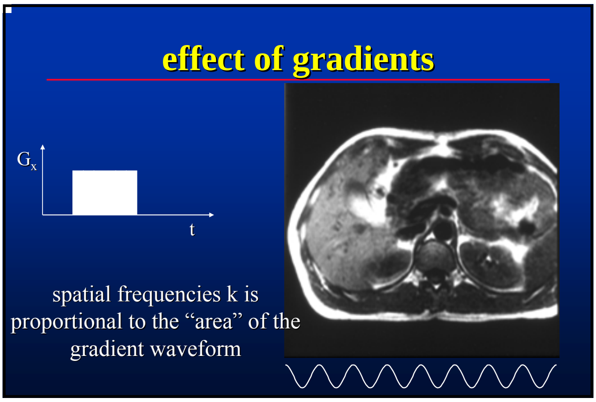


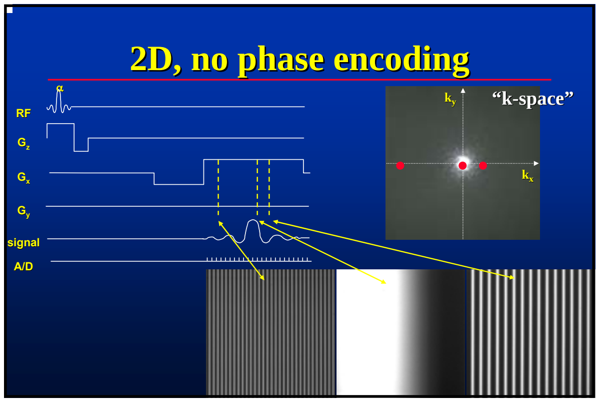


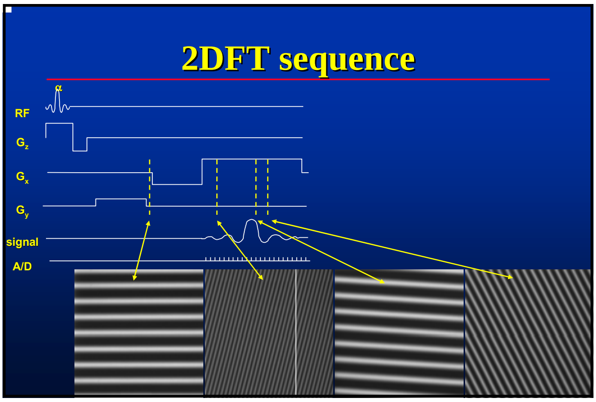
effect of gradients

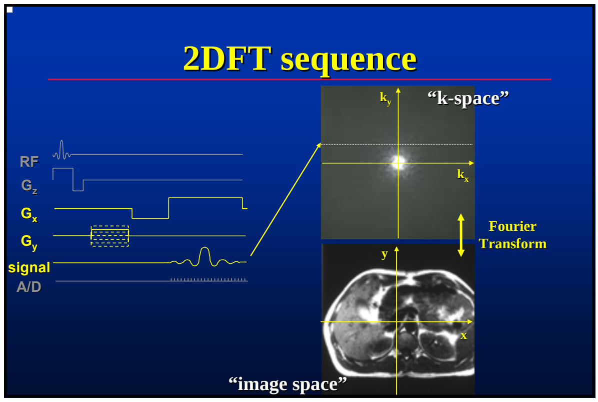


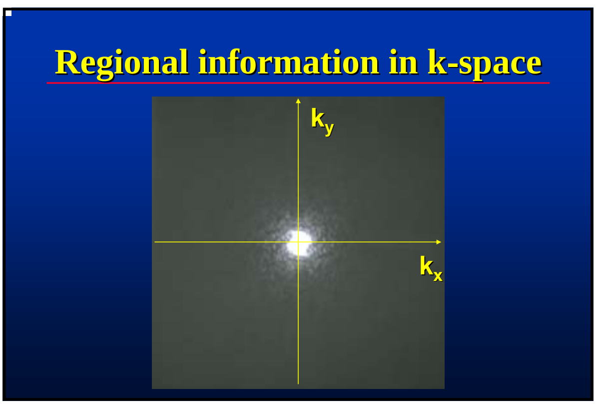


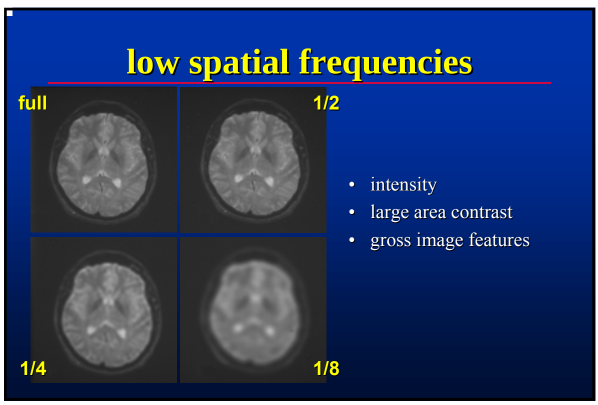

effect of gradients
Gx
t
spatial frequencies k is proportional to the “area” of the gradient waveform


2D, no phase encoding
α
RF
Gz
Gx
Gy
signal
A/D
ky
“k-space”
kx


2DFT sequence
α
RF
Gz
Gx
Gy
signal
A/D


2DFT sequence
RF
Gz
Gx
Gy
signal
A/D
ky
“k-space”
kx
Fourier Transform
y
x
“image space”

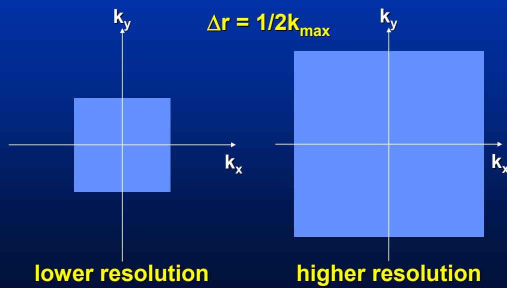

Regional information in k-space
ky
kx


low spatial frequencies
full
1/2
1/4
1/8
• intensity
• large area contrast
• gross image features

high spatial frequencies

- edges
- detail
- sharpness

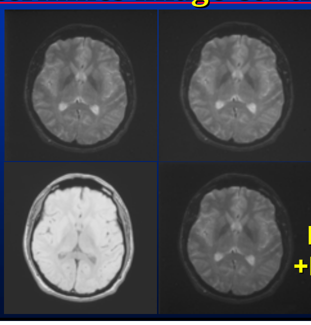
spatial resolution



The center of k-space determines image contrast

T2W

1/2



PDW

Low(T2W)
+High(PDW)

Conclusions

- nuclei with magnetic moment & angular momentum
- $B_0 \rightarrow$ longitudinal magnetization M_z
  - equilibrium M_z µ proton density & B_0
  - M_z grows toward equilibrium with time constant T_1
- Excitation with B_1 rotating about B_0 at Larmor frequency $\omega = \gamma B_0$
  - RF pulse
  - rotating frame
  - flip angle (α, 90º, 180º), direction

Conclusions

- Transverse magnetization M_t
  - perpendicular to B_0
  - rotates about B_0 at Larmor frequency
  - decays with time constant T_2
- NMR signal generated by net M_t
  - FID, immediately after RF pulse
  - decays with time constant T_2^*
  - spin echo, less sensitive to off-resonance
- Magnetic Resonance Imaging
  - localization using magnetic field gradients
  - signal is related to the Fourier Transform of the object
  - k-space